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Unique Aspects of Micromechanics in Ballistic Penetration

by P. W. Kingman

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Unique Aspects of Micromechanics in Ballistic Penetration

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Abstract

Ballistic experiments with tungsten penetrators composed of single crystals have been used to specify and constrain deformation modes in order to elucidate the role of flow and deformation mechanisms in penetration. The large differences in penetrator performance as a function of crystal symmetry are interpreted in terms of the structures observed and the basic deformation modes implied. The results suggest in very general terms the interactive role of material deformation parameters. The superior performance of the [001] orientation is attributed to the combination of yield strength with an unusually smooth lamellar flow after failure initiates. In contrast, the high yield strength of the [111] crystal is offset by the dissipation of energy in less efficient flow mechanisms and microstructural evolution. The analysis has implications for approaches to optimizing penetrator design through tailored materials and microstructures.

Acknowledgments

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1. Introduction

The material flow mechanisms occurring under ballistic regimes exert a strong influence on penetration performance. Directional properties of materials have previously been recognized as a factor in the penetration process, but understanding of their actual role has been severely limited by the complexities of both mechanics and materials.

In a prior series of experiments at the U.S. Army Research Laboratory (ARL), tungsten rods machined from crystals at specified orientations were fired into semi-infinite rolled homogeneous armor [1]. The rationale for experiments with single crystals is that effects of penetrator geometry, ballistic conditions, and material parameters such as composition, density, grain size, etc., can be minimized. All specimens can be completely identical except for the internal (crystallographic) symmetry. Crystal symmetry is fundamental in determining the microstructural initiation and modes of material flow in crystalline materials, and at high symmetry the imposed constraints are stringent and specific. While single crystals may have limited practical application, well-specified experiments can be of great value in isolating and understanding the fundamental role of various deformation modes and their constraints.

The ballistic experiments have been described previously [1]. Figure 1 graphically summarizes the results. Each crystal rod had a selected unique crystallographic direction parallel to the penetrator axis. The observed results are a strong function of crystallographic symmetry, and in contrast with quasi-static stress-strain tests, the $[111]$ (three-fold symmetry axis) single crystal was not the best performer. The $[001]$ (four-fold symmetry axis) rod actually exceeded current tungsten heavy alloy penetrators and approached the performance of depleted uranium [1].

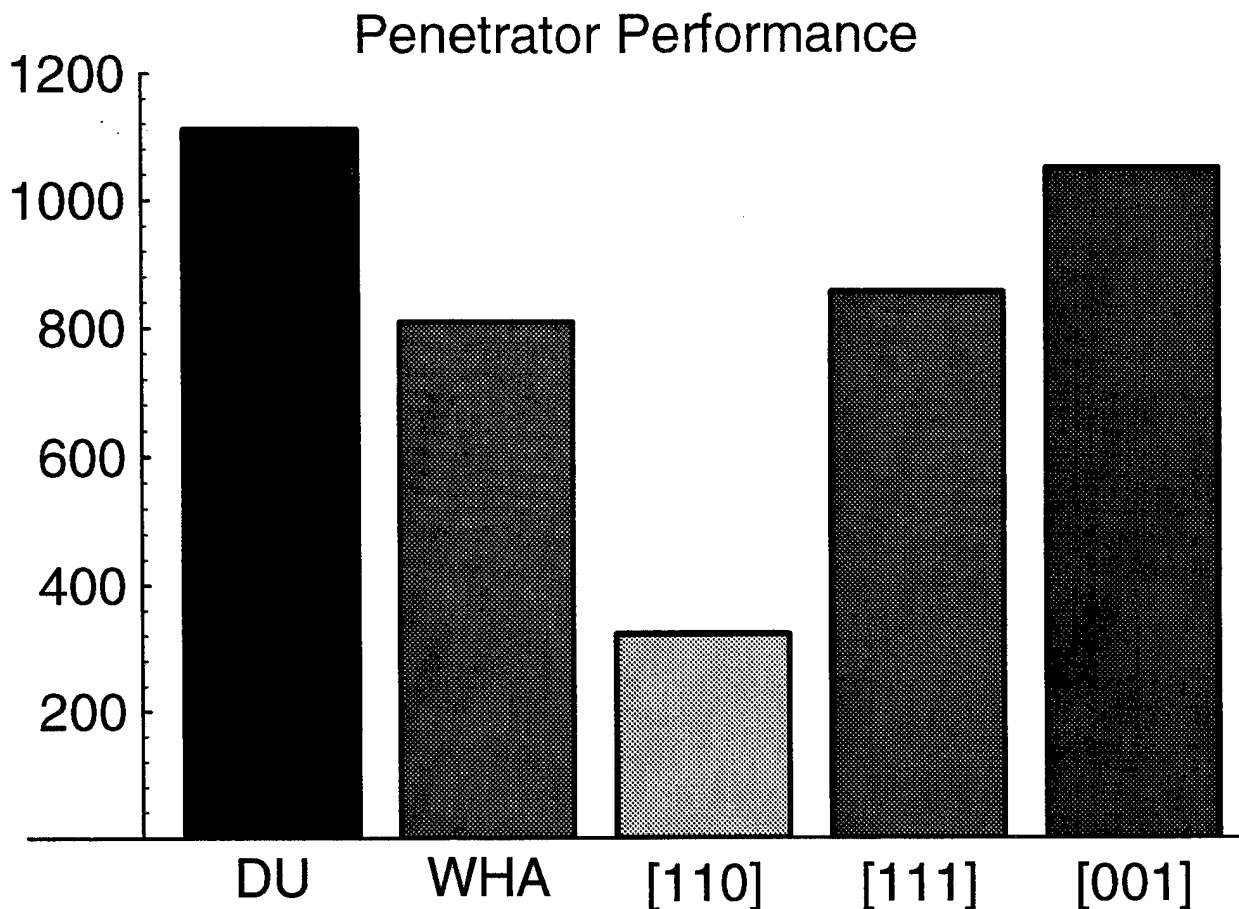


Figure 1. Results of Ballistic Tests Against Semi-Infinite RHA.

2. Experimental Approach

Axial sections of the targets demonstrated the effects of crystallographic orientation on the general flow pattern [1, 2]. The residual back end of the penetrator, typically about one diameter (~6 mm) in length, remained at the bottom of the penetration cavity surrounded by a thin layer of flowed material that extended back along the cavity walls to form a continuous hollow tube with a pattern of scroll-like foliations on the inner surface. Details of the final residual shape, the general appearance of the internal foliations, and the geometry and surface characteristics of the penetration tunnel differed for each crystal orientation, suggesting that the substantial differences in macroscopic penetration behavior originate in microscopic factors governing the initiation and continuation of material flow in the lattice.

Extensive characterization of the penetrator remnants was performed, utilizing optical microscopy and a variety of electron-optical and diffraction techniques. Diffraction data provide a basis for analyzing crystal orientation, lattice inhomogeneity (localized bending and substructure), recrystallization, grain size, preferred orientation, etc. A diffraction pattern from a small region of a single crystal can be analyzed to indicate the orientation of that region relative to the specimen axis, and visual features of the pattern can provide valuable qualitative information about the lattice distortion. The following discussion focuses primarily on the interpretation of the diffraction-based information as a key in bringing together all of the observations to form a coherent picture of the deformation process for each of these orientations.

3. Experimental Results

3.1 [110] Penetrator. This residual penetrator was completely recrystallized except for a small region at one corner of the back end (Figure 2). The material in the etched band structure is polycrystalline, and the Debye-Scherrer (D-S) rings from various regions indicated a variety of substructures ranging from sharp, equiaxed recrystallized grains to broad cold-worked rings, generally with strong texture. The rear surface of the rod was a mass of irregular surfaces, implying that the residual rod was heavily cracked and fragmented. The small remaining crystal fragment was tilted and deformed, so no useful orientation information could be obtained. The bands and cracks (probably originally axial) in the upper right portion of Figure 2 are thought to have initiated early in the process, followed later by laminar flow with extensive recrystallization. Although verification by diffraction was not possible, the appearance of the bands suggests twins, which would agree with observations by other workers [3, 4]. Figure 3 is a scanning micrograph of the layered structure in the extrusion tube. Some layers consist of relatively equiaxed grains and intergranular fractures, while the middle layer contains an extended region of cleavage. This microstructure agrees well with the flow pattern seen in Figure 2: some lamellae, possibly twin bands, developed a textured substructure which cleaved, while the surrounding material eventually recrystallized into equiaxed grains, resulting in intergranular fracture. The varied structure and appearance of the D-S rings in X-ray diffraction patterns from

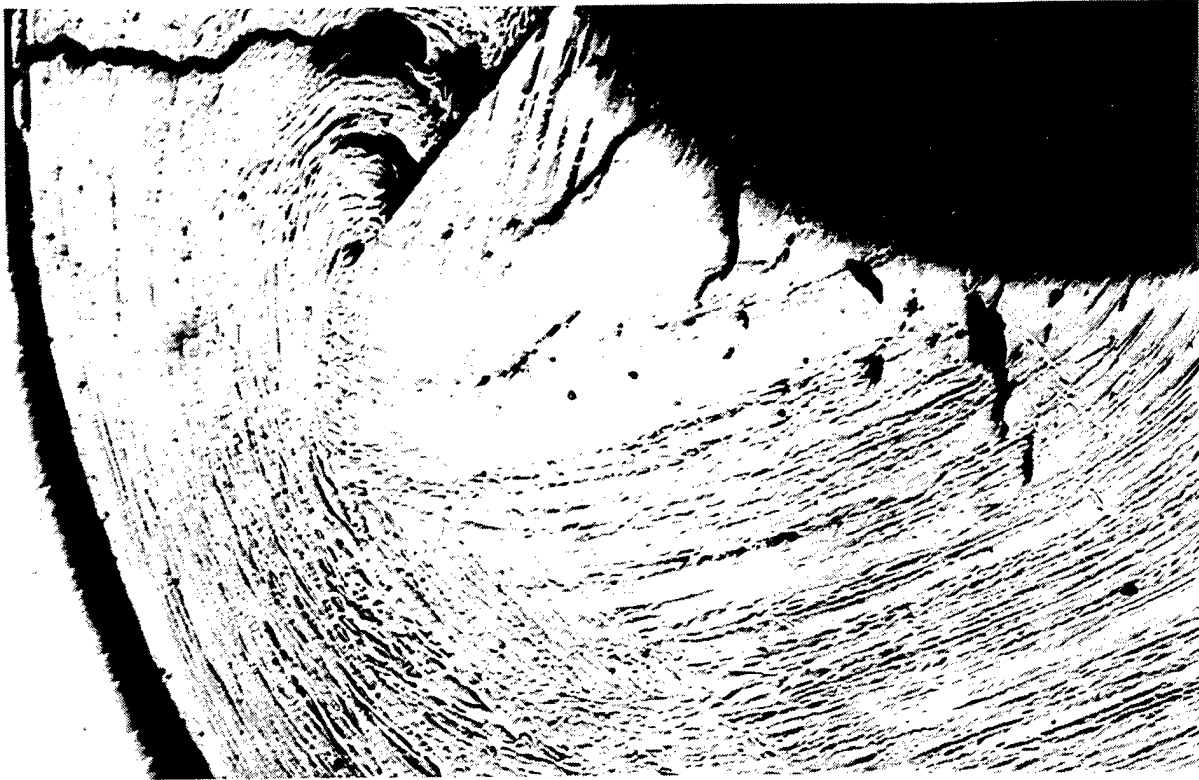


Figure 2. Axial Section of [110] Penetrator, Showing Remnant Crystal and Flow Pattern.

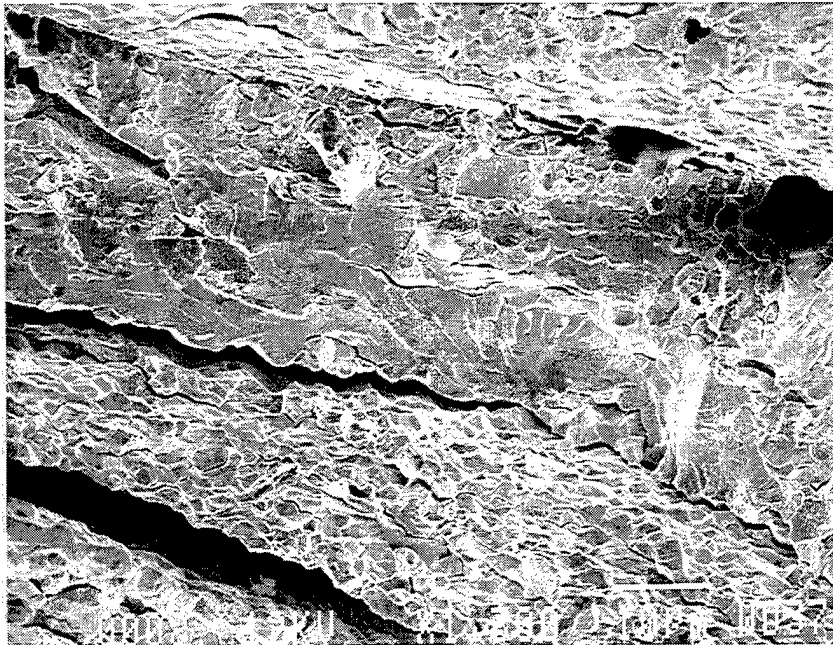


Figure 3. Layer Structure in Extrusion Tube of [110] Penetrator.

this residual also support that interpretation. The overall flow patterns and general appearance of the [110] extrusion tube are quite different from those of other orientations. The frond-like shape of the foliations suggests extensive ductile flow at this stage of the process (Figure 4).

3.2 [111] Penetrator. An axial section through the [111] residual penetrator is shown in Figure 5. Diffraction patterns showed that the well-defined, blunt-nosed residual rod (schematic inset in Figure 5) is a single crystal, with some uniform lattice distortion but little net lattice rotation. Material in the flowed regions was primarily polycrystalline, with some lamellar bands surrounded by regions of equiaxed recrystallized grains. A few relatively large lamellae, mostly embedded directly ahead of the residual rod, were still single crystals, although severely bent and deformed. These regions appear schematically below the residual crystal in the Figure 5 inset. Figure 6 shows a series of diffraction patterns from the largest crystal fragment. As a reference, the X-ray pattern at point (a) is typical of the main body of the residual rod. Diffraction patterns from points (b), (c), and (d), all within the largest fragment, showed heavily textured rings along with broad, structured discrete reflections. The crystal orientation changed continuously from point (b) to point (d). It appears that the separated segment was in the process of being forced out of the way of the oncoming rod, surrounded by material previously recrystallized.

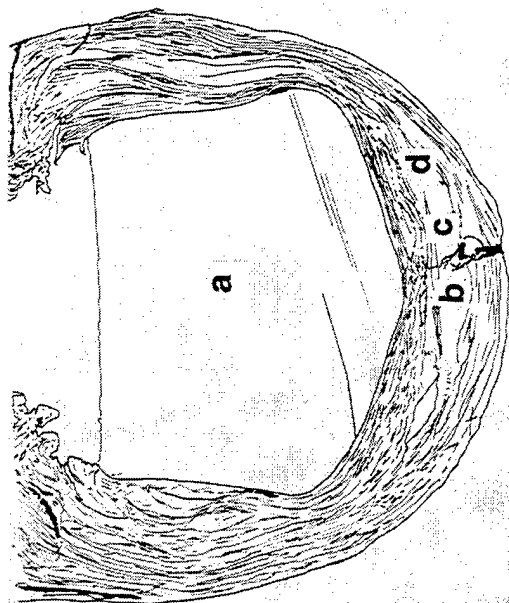
The precise nature of the few narrow bands appearing in the residual crystal could not be determined, but close examination suggests that they are flow bands whose propagation separates a crystal segment from the main rod. In the micrograph of Figure 5, a pair of closely spaced bands appears in the lower right corner. On the far right are layers of material that has already been discarded and forced out of the path of the rod. Just above the tip of the band is a small void between the rod and the discarded material, possibly opened up as the segment in the process of discard began to move to the right. We can infer that the segment below the band is just beginning to separate, the deformed and partially recrystallized region embedded directly below the rod resulted from a preceding discard, and the entire continuous layer of material surrounding the residual and extending to form the hollow tube is the result of a succession of such events.



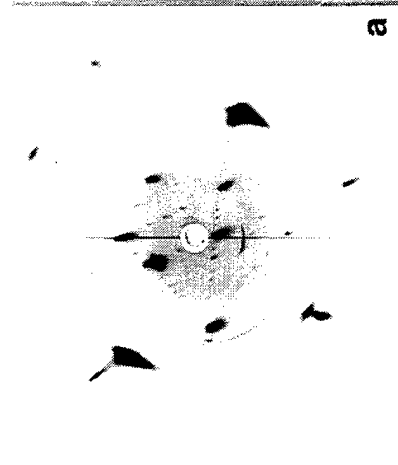
Figure 4. Axial Section: Wavy Appearance of Exfoliations in [110] Extrusion Tube.



Figure 5. Axial Section of [111] Penetrator: Flow Line Patterns and Internal Bands Near Lower Right Corner. Inset: Schematic of Residual.

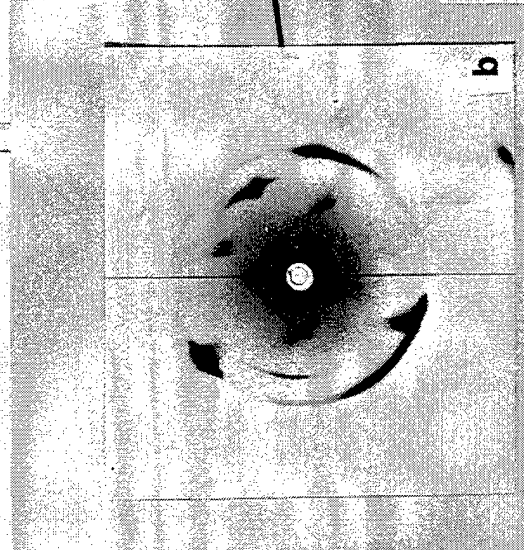
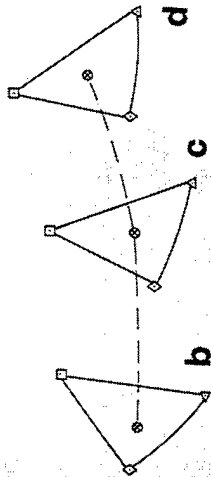


(Right) Reorientation of separated single crystal segment during radial flow at front of penetrator.

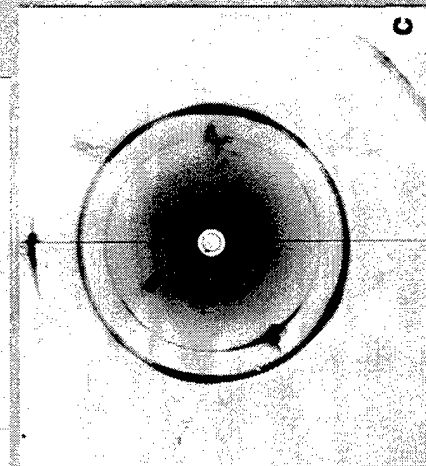


a

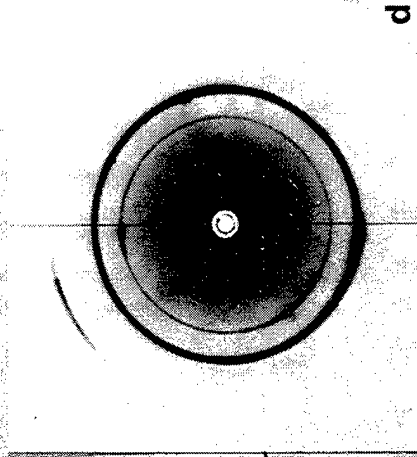
(Above) orientation of observation surface.
(Left) Diffraction pattern from center of $[111]$ residual rod (location a).



b



c



d

Diffraction patterns from locations a), b), c), in single crystal fragment embedded in flow ahead of remanent residual rod.

Figure 6. X-ray Analysis of Separated Crystal Segment Ahead of the $[111]$ Residual Rod.

3.3 [001] Penetrator. Contrasting with the [111] rod, optical micrographs of an axial section of the [001] penetrator showed no clearly outlined rod remnant. Instead, there is an assemblage of blocky segments defined by large cracks, and throughout much of the sample there occurs a fine-scale ($\sim 100\text{ }\mu\text{m}$) network of narrow, straight crack segments intersecting at right angles (Figure 7). In the central residual rod, these cracks are parallel and perpendicular to the rod axis, but in the peripheral regions they become respectively radial and parallel to the cavity interface. On the left side of the extrusion tube, this rectangular pattern could be observed within the layers and exfoliations, while on the opposite side there appeared to be sequences of voids. X-ray patterns showed the persistence of discrete crystal reflections throughout the entire nose of the penetrator and well into the extrusion tube. In the residual rod remnant, the diffraction pattern was always sharp and well-defined, but even in the macroscopically flowed regions, discrete diffraction spots could be easily distinguished. Extensive analysis throughout the specimen established that the fine cracks were parallel to {001} cleavage planes in all cases. Where the cracks continuously varied in direction, the crystal orientation also continuously rotated, as shown by the sequence of orientations at the bottom of Figure 7 (the dot on each stereogram is the pole of the observation surface). These orientations were determined from a step-sequence of X-rays across the boxed region. The trace of the (001) plane (the lower edge of the standard triangle) exactly matches the crack direction with virtually no change in the appearance of the diffraction pattern except for rotation. Along the penetrator axis directly ahead of the residual rod, the orientation was maintained and the spots were uniformly broadened without asterism. The only exceptions occurred when the diffracting region included the immediate edges of large cracks, where patterns exhibited asterism and D-S rings from recrystallized material at the interface, and at the outer surface of the sample, where a thin layer of deformed material also produced D-S rings.

Along the left edge of the penetrator, lattice rotation can be documented continuously from the nose back into the hollow extrusion tube for several rod diameters without discontinuity, until the discrete spots finally disappear in strongly textured D-S patterns.

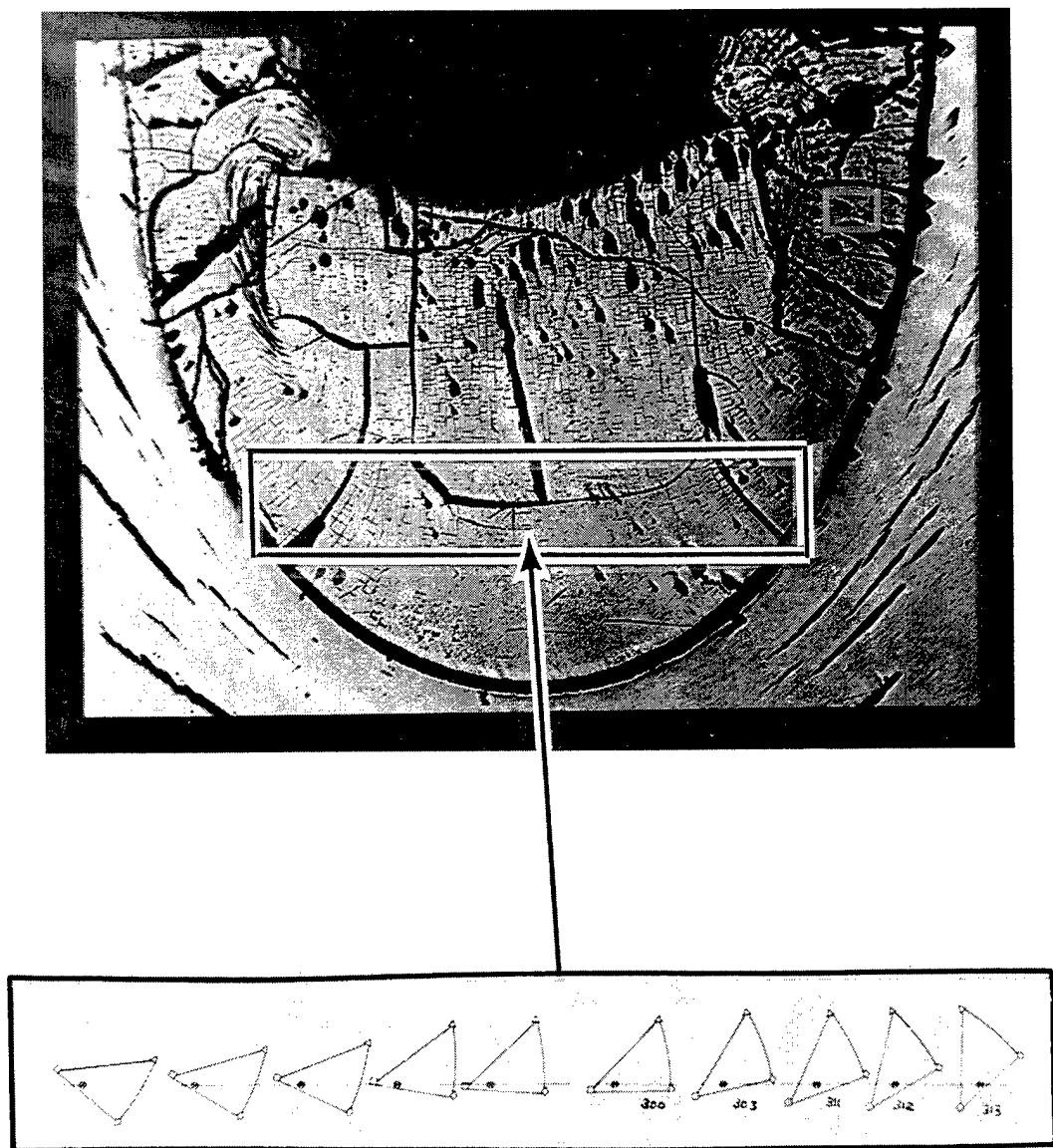


Figure 7. Stereograms of Diffraction Patterns Taken in Sequence Across [100] Peripheral Flow Region.

In the upper right corner of Figure 7, the microstructure appears inconsistent with the remainder of the sample, since the crack network is not evident. This region is shown in more detail in Figure 8a. X-ray analysis showed that above the severe inhomogeneity occurring adjacent to the residual rod, the lattice orientation abruptly changes by about 30° , so that the (001) cleavage plane is no longer normal to the rod axis. The void-like features occur because the cuboids tilt into the observation surface, and at many locations small segments were extracted during preparation. The micrograph in Figure 8 shows the changing crack patterns. On the left is a typical diffraction pattern from location "A" and the related stereogram. The dot is the pole of the observation surface, and the (100) plane is horizontal and nearly normal to the observation surface. On the right are (upper) the stereogram for region "B" and a sequence of stereograms from a traverse across the transition region "C." The accompanying typical diffraction pattern corresponds to the "double" stereogram plotted from the opposite ends of each elongated diffraction spot. The orientation of the crack patterns in the transition region can be seen to change in parallel with the (100) trace in the stereograms, which indicate (as does the shape of the spots) a single-axis rotation about the observation normal.

Examination of a second [001] penetrator further elucidated the nature of this rotation and the true three-dimensional character of the deformation process. This penetrator cracked during flight and impacted the target in two closely spaced coaxial segments, and thus the residual did not have full integrity. After sectioning, most of the residual dropped out intact, leaving a partial shell of deformed layers adhered to the concave surface at the bottom of the penetration tunnel in the target block. Figure 9a is a scanning image of the convex surface of this extracted fragment at low magnification (nose pointed down). The convex surface appears covered with tabular rectangular packets, often rotated relative to one another (Figure 9b). Although a thin surface layer was deformed and partially recrystallized, discrete diffraction spots were distinctly visible in these packets (Figure 9c). It appears that material flow in the [001] crystals is not purely radial but that the flow packets of {001} layers also have a rotational degree of freedom about the normal to the packet. This would imply a very substantial degree of independence for these entities after cleavage. The rectangular edges of the packets also appear to be defined by {001} cleavage planes, but this could not be directly confirmed.

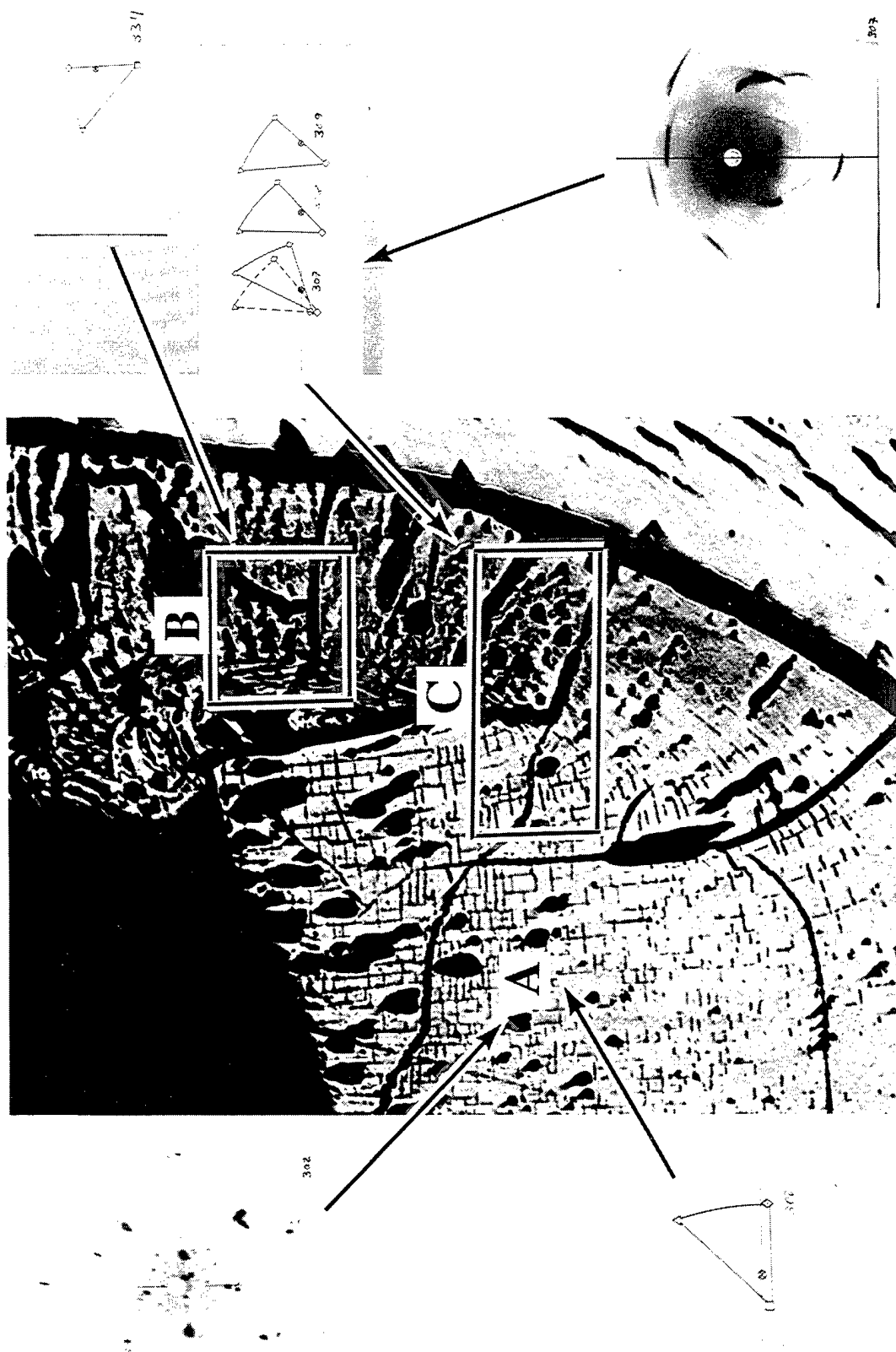


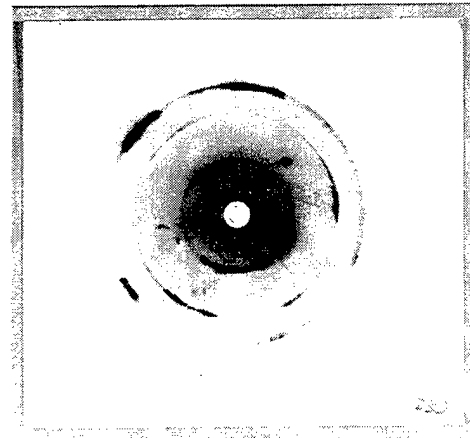
Figure 8. Partial Axial Section of [100] Penetrator With Orientation Analysis for Selected Regions.



Down



B



C

Figure 9. Convex Surface of [100] Penetrator Fragment (nose down): (a) Overview; (b) Tabular Packets; (c) Diffraction Pattern.

4. Discussion

From the experimental observations, it is evident that the operative microstructural processes are unique for each symmetry orientation.

In the [111] crystal, three $\langle 111 \rangle$ directions occur symmetrically at 70.5° from the rod axis. Resolved shear stresses on dislocations having these three Burgers vectors are thus relatively low, resulting in a high yield strength, while ample generation of dislocations available for interaction enhances work hardening. The tip of the residual is blunt, and it appears that relatively thick segments of material separate from the rod along narrow shear localizations and are forced outward toward the cavity walls along the blunt surface angle of the rod remnant while undergoing extensive working and recrystallization. The three-dimensional geometry of the separating segments is undetermined, but the cavity walls, which appear wavy in the axial section, are actually covered with discrete craters rather than having a circumferential undulation. All of these features suggest a less-than-smooth process. This sample was also the only one to possess a distinct surface layer of diffused iron from the target block, as well as iron solidified inside open cracks, indicating substantial heat generation during penetration. All of these observations suggest relatively greater diversion of forward kinetic energy into heating, hot working, and microstructure evolution as radial mass transfer and penetrator erosion take place.

For the [110] orientation, both imaging and diffraction results indicate that the penetrator material has repeatedly recrystallized, deformed, and recrystallized again. Classically, [110] bcc crystals have a high yield strength but do not work harden because the necessary dislocation reactions are unavailable due to symmetry. At high impact velocities, twins may occur [3, 4]. The bands seen in the micrographs were too fine and inhomogeneous to analyze by X-ray diffraction, but the possibility that both twins and axial cracks occurred early in the deformation process would agree with other observations on bcc materials. The consequent loss of integrity could account for the poor penetration in spite of the ductile flow.

In the [001] penetrator, with four-fold symmetry, all four $\langle 111 \rangle$ directions are equally stressed, creating large numbers of dislocations able to react with one another. One possible reaction is the Cottrell reaction [5]

$$\frac{1}{2} a [111] + \frac{1}{2} a [\bar{1}\bar{1}\bar{1}] \rightarrow a [100], \quad (1)$$

which produces a sessile dislocation. This sessile dislocation is associated with the initiation of {001} cleavage cracks in bcc crystals oriented with a tensile stress axis along the [001] direction [5, 6].

Under impact conditions it can be reasonably speculated that a large distribution of dislocations would immediately be created and move only a short distance before interacting to create an extended array of sessile dislocations. This array would then inhibit work hardening and create nucleation sites for cleavage cracks as the deviatoric stresses increase and material flow is initiated. The smooth lamellar bending and shear, along with the relative absence of substructure, complex lattice distortion, and recrystallization in X-ray patterns from much of the peripheral flow region, indicate that relatively little work hardening occurs in the [001] penetrator. In contrast with the [111] hole profile, the [001] penetration tunnel is narrow and exceptionally smooth, and there is less material interaction between the penetrator and the target. Rather than discontinuously shedding finite material segments, the [001] rod is postulated to flow by a smooth quasi-continuous process in which small, finite lattice elements defined by (001) cleavage planes undergo a combination of lamellar bending and rotation during flow with little internal disturbance. This is a highly efficient process, permitting maximum partition of energy into forward motion. The persistence of the rectangular crack pattern through the curved foliations in the extrusion tube is strong evidence that lamellar flow of finite entities with minimal lattice disruption is the dominant deformation mode and that continuous reorientation of these discrete entities was complete before any recrystallization occurred. The observed rotation of the lamellar packets also suggests a substantial degree of independence for these entities during deformation.

Recently, ballistic experiments have been done with oriented polycrystals composed of individual grains having a symmetry axis oriented along the penetrator axis, with unconstrained rotations about the axis [7]. Differences between the major symmetry directions still exist but are smaller, and the [001] specimens perform less advantageously. Since the (001) cleavage is still theoretically normal to the axis in all grains, it is not clear whether the decrease in performance derives solely from mismatch obstacles to direct radial shear or whether the additional rotation of the packet about the normal to the cleavage plane may be essential to easy flow, and may be constrained in the polycrystal.

5. Conclusion

Ballistic penetration tests using rods machined from tungsten single crystals at specified orientations have shown that crystallography, which governs microstructural failure and flow mechanisms, is a strong determinant of penetration behavior. As previously noted by Magness and others [8, 9], classical quasi-static data do not necessarily imply similar performance in ballistic penetration. The excellent performance of the [001] orientation has been shown to result from a unique deformation mode in which work hardening is suppressed and flow initiates at microscopic inhomogeneities. In this mode, small but distinct crystal entities shear and flow with minimal internal deformation. Although adiabatic shear does not occur, this mode similarly activates an energetically efficient, uniform flow. Maximizing the fraction of total energy partitioned into forward penetration results in a deep, narrow, smooth-walled penetration cavity similar to that produced by depleted uranium (DU).

Single-crystal experiments provide a unique opportunity to specify highly constrained deformation modes. Basic material mechanisms are thus isolated without introducing additional material variables. Understanding these fundamental mechanisms will lead to a basis for designing novel materials and composites for future application.

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